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Enabling Future Sustainability Transitions

An Urban Metabolism Approach to Los Angeles

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Summary

This synthesis article presents an overview of an urban metabolism (UM) approach using mixed methods and multiple sources of data for Los Angeles, California. We examine electric energy use in buildings and greenhouse gas emissions from electricity, and calculate embedded infrastructure life cycle effects, water use and solid waste streams in an attempt to better understand the urban flows and sinks in the Los Angeles region (city and county). This quantification is being conducted to help policy-makers better target energy conservation and efficiency programs, pinpoint best locations for distributed solar generation, and support the development of policies for greater environmental sustainability. It provides a framework to which many more UM flows can be added to create greater understanding of the study area's resource dependencies. Going forward, together with policy analysis, UM can help untangle the complex intertwined resource dependencies that cities must address as they attempt to increase their environmental sustainability.

Introduction

With the increased interest in cities that has emerged in the last few decades as a result of an unprecedented shift in human populations to urban dwelling, impacts of cities on the environment and the potential to reduce their inputs have revived an interest in the concept of urban metabolism (UM). UM has been advanced as a way of creating greater empirical knowledge in order to help cities become more sustainable by quantifying urban flows and sinks. From quantification of flows, baseline metrics can be used to support program evaluation and target reductions policies (Pincetl et al. 2012; Keirstead and Sivakumar 2012; Kennedy et al. 2007). Obtaining data at a sufficiently downscaled level, so as to accurately and specifically characterize energy and water use in a useful manner (parcel level), is often difficult, given customer privacy protocols and the reluctance to share these data by utilities and other stakeholders in the United States. Yet, parcel-level data can provide important insights into an urban metabolism when correlated with building age, size, use, and sociodemographic characteristics, even if the final results are aggregated to such units as census blocks to ensure protection of individual customers' identity. Other regionally specific data, such as economic activity data, are highly sensitive and difficult to obtain. Transportation data can be patchy, and some data, such as water use, may not be metered at all. Given the difficulty of obtaining parcel data, regional economic data, and other data that can help quantify regional flows specifically, UM analyses in the United States are often developed at the whole city level, downscaled from national- or state-level aggregate data, or modeled (Huang and Chen 2009; Miller et al. 2012). Detailed (i.e., parcel-level) data can enable detailed analyses across building types in a city, or by building use, by census characteristics, by industry using the National American Industry Classification System (NAICS) codes (the standard used by federal statistical agencies in classifying industries), or other types of categories and spatial scales.

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With parcel-level and annual or monthly billing data provided by utility companies, it is then possible to create actual baselines of energy and water use that can then be used to evaluate changes in the use of resources over time. In this way, success of conservation programs, greenhouse gas (GHG) reductions initiatives, infrastructure investments, and equity impacts can be evaluated, and policy can be adjusted to achieve goals.

Further, linking these baselines and change over time with the soft infrastructures of management (rules, codes, norms, policies, and procedures) can provide insights into what works and what does not, and for whom. For example, a neighborhood-level evaluation of electricity use can help guide investments in distributed solar generation to relieve the grid, especially in peak energy demand periods.

UM studies have been undertaken for several decades. Driven by his concern for deteriorating water and air quality, originally, Wolman (1965) quantified the gross energy, material, water, and waste fluxes for a hypothetical U.S. city of 1 million inhabitants. This was a seminal study that demonstrated the usefulness of a metabolism framework to assess the sustainability of urban systems. Interest in these kinds of questions has produced important, and often neglected, work. For example, the Boyden and colleagues (1981) case study of Hong Kong, as part of the Man and the Biosphere United Nations Educational, Scientific and Cultural Organization (UNESCO) project to promote integrative ecological studies of human settlements, examined how to create cities without seriously damaging ecosystems. It was a milestone in establishing a study and description of human settlements in terms of the interrelationships of biotic, cultural, physicochemical, and societal impacts. Because of Hong Kong's special status at the time, data were relatively available. The study was an important contribution to thinking about impacts of humans on ecosystems, and, subsequently, multiple variations of this fundamental concept have been applied to assess the metabolism of various cities and even countries (cf. Newman [1999] for Sydney, Australia; Huang and Chen [2009] for Taipei, Taiwan; Liang and Zhang [2011] for Suzhou, China; Miller et al. [2012] for India; Caprotti and Romanowicz [2013] for Masdar, Abu Dhabi). Kennedy and colleagues (2012) examined GHG emissions inventories for Berlin, Boston, Greater Toronto, London, New York, and Seattle to assess emissions trends between 2004 and 2009. They found that each city was reducing emissions on a per capita basis, and that all except Boston and Seattle were reducing emissions in the aggregate as well. Kennedy and colleagues (2010) also consolidated diverse studies and enabled a comparative metabolism analyses for the cities of Brussels, Tokyo, Hong Kong, Sydney, Toronto, Vienna, London, and Cape Town. Except for Toronto, increasing per capita metabolism was observed in all cases with respect to water, wastewater, energy, and materials. Huang and Chen (2009) point to the importance of UM to elucidate relations between land-use change and UM using emergy analysis (see Pincetl et al. [2012] for a literature review and discussion of emergy). In this study, we use life cycle assessment (LCA) analysis to better understand the resource inputs into the Los Angeles region, which clearly have nearby and far-reaching land-use change impacts. We see this current study as an additional step forward in operationalizing UM for policy change.

UM studies are increasingly being used to determine the efficacy of policy interventions, develop energy and carbon assessment metrics, and develop urban GHG inventories. Some studies use health outcomes as an objective for designing and planning low-carbon communities and consider the influence of supply-chain characteristics on urban infrastructure GHG emissions with varying degrees of detail (Chavez and Ramaswami 2013; Chester et al. 2013; Circella et al. 2013; Kennedy et al. 2012; Ramaswami et al. 2012; Sperling and Ramaswami 2012). Yet, there is a sense that urban metabolism has not reached its full potential (Kennedy et al. 2007; Keirstead and Sivakumar 2012; Pincetl et al. 2012). UM can reveal a great deal about the efficiency of economic activities in an urban area with comparative data on energy use by similar NAICS codes, and it can help in understanding sectors with high GHG emissions and the reasons behind these environmental impacts if coupled with detailed life cycle analysis. UM can provide insights about embedded energy in the urban fabric and patterns of energy use over time when there are longitudinal data. This type of analysis is critical to efficiently reduce energy use over time.

As mentioned above, there are obstacles to obtaining data in the United States. State- and local-level economic input-output analysis (IOA) is often lacking, and life cycle analysis of economic activity at a state or local level is virtually nonexistent. Hence, calculating local economic impacts accurately is difficult for most places in the United States. City or regional solid waste flows are also poorly disaggregated, either by type or generator. So, for example, calculating specific quantities of recyclable materials, such as cardboard, by generator type (e.g., big box retailers) is only possible through modeling. Analysis of the amounts of solid waste generated by neighborhoods faces similar data issues. These are important obstacles to targeting waste reduction policies. Further, different flows are monitored and collected at different levels of aggregation, whereas others are not collected at all. For instance, whereas electricity, water, and natural gas use is collected at the parcel level in Los Angeles, some cities in California still have no residential water meters. Additionally, utilities are reluctant to share customer data and often destroy data after only a few years. Thus, to conduct comparative analysis longitudinally is difficult if one wishes to assess the impacts of energy conservation and/or efficiency programs, an important evaluation to conduct. Instead, programs are implemented on modeled data with no verification on the ground.

California has spent over $13 billion of rate-payer funds on energy conservation and efficiency programs since 2002, but no baselines of use had been established, and no assessment of actual success or failure has been conducted. Data may also not be consistent across utilities in the same region, and they may not use the same types of identifiers. Additionally, some data may be available for longer periods than others, and units may vary among the utilities as well.

Other scale and data issues exist as well. Boundary definitions for GHG emissions attributions continue to be difficult to establish; economic activity statistics may also be difficult to obtain at the local and regional levels and in corresponding time horizons to other collected data. Impact Analysis for Planning Data (IMPLAN), which provides IOA in combination with ZIP codes (postal code of the U.S. Post Office of five decimal numerical digits), uses annual national economic data. In this study, we combine IMPLAN economic data for 2008 with the Carnegie Mellon Economic Input Output-Life Cycle Analysis that is California specific, but based on 2002 IMPLAN data. All these challenges are important to recognize: Some of them may not make a difference in the fundamental understandings of flows; others will be more significant. At this point, given the quality and status of the data, UM must remain somewhat opportunistic and will not be as methodologically homogeneous as would be most optimal.

We advocate parcel-level analysis, where possible, because it will best capture important nuances and differences within cities and regions. It also has the most potential for revealing variations that are obscured when scaling up and thus can result in better policy to target behavior, identify flows that are to be changed or shifted, and create long-range policy goals. In the next sections, we discuss our assumptions, methods, and preliminary findings.

We readily recognize that the term urban metabolism is problematic across scientific disciplines, most notably the biological sciences. An organism has a metabolism, whereas a city is more analogous to an ecosystem wherein many species interact (Golubiewski 2012). We defer, in this article, to industrial ecologists' appropriation of the term, and to its historic use in the literature, including in some planning circles. We concur, however, that a city or urban region functions more like an ecosystem than an individual organism. Moreover, we recognize the limitations of the biological analogy for cities more generally (Bettencourt 2013).

Theory and Motivation

The theoretical perspective taken for this project is based on systems theory (Meadows 2008). Systems theory states that there is a relationship between structure and behavior. Cities are created by social systems and rely on complex networks of human-made systems to supply them. In a sense, they are self-referential. They result from, and also constitute, sociometabolic regimes (Haberl et al. 2011) that extend beyond the city itself (Boyden et al. 1981). The ultimate purpose of UM research is to describe and understand those sociometabolic regimes such that reductions in the use of resources and associated environmental impacts can be achieved. We add to this the importance of equity considerations. Thus, one goal of establishing a city or region's metabolism is to quantify the material substrate on which a city depends and to unravel the policy and behavioral drivers as well as the differences that might exist among socioeconomic groups not just of energy and water use, but also of associated built environment attributes: size of building; age of building; building shell; and use. Businesses may also differ in efficiencies, and understanding those ranges can help target programs to improve entire sectors, to make them both more efficient and also potentially more competitive. Although fulfilling these comprehensive goals is beyond the scope of this specific project, better documenting the environmental flows and how they are regulated, how access to data itself is regulated or codified, and the effects of land-use patterns in the urban landscape do help to start connecting policies to outcomes, structures, and behavior and resource use. It can help to identify the areas where the most attention to policies should be given for the unraveling of resource-intensive practices. This can include where the deployment of distributed generation is likely to have the most effect—for example, in reducing peak loads in the summer—or where water conservation programs are most needed. Analyzing embedded energy in the urban fabric can also help determine priority areas for infill development (making the most of already expended materials), and to associate building energy use with embedded energy in the buildings. Finally, whereas we do not claim to have achieved a full system analysis with this project and in our initial findings, the aim of UM, so it can achieve its promise, should be to create more system understandings of urban systems.

Advancing Urban Metabolism

This research accounts for energy, water, and material inputs as well as GHG and solid waste outputs for Los Angeles County and City. The ultimate aim of the research is to account for county-wide energy and water flows, to match this to embedded energy, parcel assessor data, sociodemographic data, and general policy drivers. Policy drivers may include legislation, agency rules, and rate settings, as well as codes and conventions.

As described above, our data vary in scale, from parcel level (for water use in Los Angeles City) to ZIP+4 (five-digit postal code plus four additional digits that correspond to a more specific location) for the city of Los Angeles electricity use, to six waste sheds for the city of Los Angeles and city level for the other cities in the county, to county levels for GHG emissions accounting. This is a result, in part, of the difficulty in obtaining data from utilities, as well as the timing of data acquisition. Figure 1 describes the boundary of the urban system we are analyzing.

Methods for Analysis

Electricity and Greenhouse Gas Accounting for the County of Los Angeles

The energy and GHG analysis of Los Angeles was developed through assessments that tested several resolutions of data aggregation. In this research, we used electricity consumption

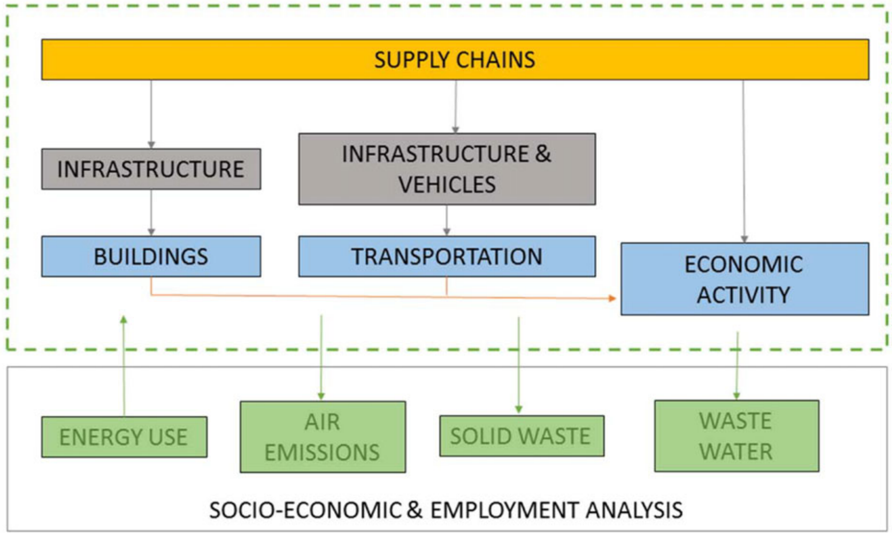

Figure 1 Boundary of the urban metabolism analysis of Los Angeles County.

data that the Los Angeles Department of Water and Power (LADWP) provided at the ZIP+4 level of spatial resolution. We quantified the electricity for building operations for 32 building classifications, through the analysis of 4.5 million buildings in Los Angeles County. To do this, we integrated electricity consumption data obtained from the utility company with detailed land-use information obtained from the Los Angeles County Assessor's data and additional information obtained from other data sources (e.g., sociodemographics from the 2010 U.S. Census and American Community Survey [ACS] 5-year estimates [2006–2010] and detailed geomorphological and climate data), through the creation of 450,000 energy analysis zones (EAZ). These calculations provided an estimate of county-wide building electricity GHG emissions (see Circella et al. [2013] for a more complete discussion of the methodological approach developed in this part of the project). This analysis differs from VandeWeghe and Kennedy (2007) in that we were able to obtain actual energy-use data from the utility, albeit aggregated by ZIP+4, rather than by developing estimates.

The effects of several variables, including income, climate zones, housing characteristics (the unit square foot size, the age of the building, the type of building—single- or multi-family—and so forth) were assessed for the energy data set created at the EAZ level using the LADWP electricity consumption data. Energy consumption for residential, commercial, and industrial buildings was determined and normalized by floorspace and person. Linear regression models investigate the impact of socioeconomic drivers of energy consumption (see Circella et al. [2013] for additional details). By analyzing across the aforementioned urban characteristics, this longitudinal data set provides a temporal and geographical understanding of energy use. To date, most city-wide building energy-use estimates rely on building energy models calibrated with regional data (Howard et al. 2012), and many approaches have been used to model various aspects of energy supply and demand (Jebaraj and Iniyan 2006; cf. Circella et al. [2013] for a broader literature review), but none, to our knowledge, have had the benefit of longitudinal data.

Second, the energy and GHG impacts of economic activity were quantified by combining IMPLAN data with a California-specific environmental input-output LCA model (CA-EIO-LCA) created for the California Air Resources Board (Masanet et al. 2012). CA-EIO-LCA tables estimate the energy resources required for, and the environmental emissions resulting from, economic activities. The fitting of California-level data to Los Angeles was completed by adjusting electricity fuel mixes to reflect LADWP and Southern California Edison generation portfolios (Southern California Edison serves the portions of Los Angeles County that do not have municipal utilities). The CA-EIO-LCA model assesses the economy as 428 sectors, each corresponding to a cluster of NAICS codes. The joining of economic flows with CA-EIO-LCA impacts produces a *region-specific* assessment of environmental outcomes from economic activities. The outcome shows how industries and other economic activities in Los Angeles County produce impacts directly and indirectly (i.e., in the supply chain). The impacts of a manufacturing process may release emissions at the manufacturing plant itself, but also trigger supply-chain activities that may occur outside of the county, state, or even country. This analysis needs now to be scaled to an even higher level of resolution (e.g., at the parcel level). However, the ZIP+4 method with the CA-EIO-LCA is already more accurate than using national-level data to impute local environmental outcomes. Regional-level data/EIO-LCA data is a significant national data gap. It exists for California as a result of funding from the state's Air Resources Board, but it is not available for other states and does not use current economic data. These lacunae are particularly significant for accurate GHG accounting into the future across the nation.

Table 1 Greenhouse gas emissions associated with electricity consumption for building operations by building type, including grid losses, in Los Angeles County

Floorspace type	*Total adjusted emissions (lb CO_2-eq)*	*Total adjusted emissions (metric tons CO_2-eq)*
a) Residential sector		
SF residential[a]	12,156,000,000	5,514,100
SF residential with pool	3,976,600,000	1,803,800
MF residential[b]	9,067,900,000	4,113,100
Total residential sector	**25,201,000,000**	**11,431,000**
b) Nonresidential sector		
Developed amusement park space	205,290,000	93,116
General commercial	12,293,000,000	5,575,900
Government operations space	621,010,000	281,680
Office space[c]	7,678,500,000	3,482,900
Hospital space	1,418,700,000	643,510
Mall and big box retail space	3,852,200,000	1,747,300
Mixed-use space	1,747,600,000	792,700
Primary K to 12 education space	1,749,800,000	793,680
Secondary education space	373,750,000	169,530
Religious space	697,960,000	316,590
Warehouse and distribution space	7,007,100,000	3,178,400
Industrial space[d]	13,052,000,000	5,920,300
Total nonresidential sector	**50,697,000,000**	**22,996,000**
Total in Los Angeles County	**75,898,000,000**	**34,427,000**

[a]Includes urban mobile homes.
[b]Includes apartments, joined, and group quarters residential.
[c]High- and low-density office space.
[d]Light and heavy industrial space.
SF = single-floor; MF = multi-floor; K = kindergarten; lb CO_2-eq = pounds carbon dioxide equivalent.
Source: Data from Circella and colleagues (2012).

Life Cycle Assessment of the County's Built Environment

UM studies can also assess the impacts of the built urban infrastructure itself. For the Los Angeles study, we quantified county-wide life cycle effects of providing roadways and buildings. This project joins UM and LCA to establish a connection between how infrastructure systems have been deployed and managed and the activities in the city that are thus enabled (see Chester et al. [2012] for further discussion of these methods, underlying data, and assumptions). Building and road infrastructure condition how people move and use buildings (Parrish and Chester 2014). Broad streets encourage automobile use—single-family neighborhoods do as well—and each type of building and road is the result of energy expenditures and induces more energy expenditures. These investments frame what emergent behavior can result. That is, in places built for automobile transportation, walking or biking is implicitly discouraged and often difficult. The emergent behavior is driving a car. A methodology was developed to quantify the life cycle impacts of building infrastructure and paved surface areas (roadways and parking) across the county and over time (additional methodological detail for these analyses are available in Fraser and Chester [2013] and Reyna and Chester [2013]) that have shaped current, and constrained future, behavior. The analysis considers major development of the city starting in the early to mid-1900s through the present. It was performed at the individual building (using county assessor parcel data) and roadway link (determined by categorizing and measuring all the roads of the county based on the Thomas Brothers map of the county). Prototypical building models were developed for three time periods (pre-1950, 1950–1990, and 1990–2012), and the corresponding material requirements, energy, and environmental outcomes for each were estimated (Reyna and Chester 2013; Athena 2012). A historical construction, maintenance, and reconstruction model was developed for roadways and highways (see Fraser and Chester [2013] for additional methodological detail). The model is developed on top of the pavement life cycle assessment tool for environmental and economic effects (PaLATE) (Horvath 2003) and uses network geographical information systems (GIS) data to estimate the material, energy, and environmental impacts for each roadway link in the county. UM research has not yet explored the connection between embedded infrastructure

Table 2 Description of the dependent and independent variables by bimonthly period used in the regression models to analyze determinants of residential water consumption

Variable	*Definition*	*Unit*	*Source*
SFR water use	Single-family water use per household per bimonthly period	HCF/hsld/bimonthly period	LADWP
Average household size	Average number of persons per household	Persons/household	U.S. Census 2000/2010
Median household income	Median household income scaled by 1,000 (bimonthly)	Inflation-adjusted $2,000/hsld	U.S. Census 2000ACS 2006–2010
Grass area percentage	Percentage of grass landcover area (constant)	%	McPherson et al. (2011) landcover database (2002–2005)
Bi-monthly total precipitation	Cumulative daily precipitation	Mm	LADPW gage stations
Average daily maximum temperature	Bimonthly average of the daily maximum temperatures	°C	NCDC gage stations
Cumulative EVI	Sum of 16-day EVI values per bimonthly period	[0–1]	MODIS Terra (250 m, 16 days)
Marginal block prices	Tier 1 and 2 rates per bimonthly period (lagged by one bimonthly period)	$2,000/HCF	LADWP
First tier usage block	Bimonthly quantity of water allocated for the first tier averaged per household	HCF/hsld/bimonthly period	LADWP

Note: Variables are calculated at the census tract level for each bimonthly period within the 2000–2007 fiscal year period.
SFR = single-family residential; EVI = enhanced vegetation index; HCF = hundred cubic feet; hsld = household; Mm = megameters; LADWP = Los Angeles Department of Water and Power; ACS = American Community Survey; NCDC = National Climatic Data Center; m = meters.

Source: Data from Mini (2013).

impacts, let alone emergent behaviors engendered by the infrastructure. Changing infrastructure to elicit different behavior (such as bicycle riding or transit ridership, rather than driving) is costly, time-consuming, and requires public will. Thus, the existing infrastructure can be said to cause path dependencies that are hard to change. It is anticipated that this life cycle approach will enable UM practitioners to better understand how infrastructure services condition behavior and may reinforce policy decisions.

Water Use for the City of Los Angeles

Single-family residential (SFR) water consumption data were provided by LADWP for the period January 1, 2000 to December 31, 2010 at the parcel level. The initial database contained approximately 480,000 individual residential customers identified by census tract numbers. Sociodemographic and economic data were collected from the 2010 U.S. Census and ACS 5-year estimates (2006–2010) at the census tract level (U.S. Census Bureau 2010). Average household size, median household income, and climate data were considered (see Mini [2013] for more details). With address-level data, aggregated to protect customer privacy, water-use mapping was conducted for single-family residences in the city of Los Angeles for 10 years. These findings were also correlated with watering restriction programs during periods of drought to assess whether voluntary or required water conservation was more successful and in which rate tier.

Remote sensing imagery was used to determine the normalized difference vegetation index (NDVI)—density of greenness—over the 10 years and seasonally, and correlated to periods of drought and different water-use restriction programs. In addition, billing tiers were considered in the analysis. From these data, researchers ascertained the drivers of water use across Los Angeles neighborhoods, the amount of water used on outdoor landscaping, and the impact of drought restrictions (voluntary and mandatory) on water use and on the greenness of the landscaping across the city.

Solid Waste Flows

Solid waste flows are an important part of UM; arguably, they represent the resources that are inefficiently metabolized

Table 3 Regression coefficients from the random effects model for key determinants of residential water consumption

Dependent variable ln(SFR water use per household per bimonthly period)		*By water use level*			*By income level*	
Variables	*All*	*Low*	*Medium*	*High*	*Below median*	*Above median*
Average household size	0.0032	0.0696*	−0.032	0.0354	0.0693*	0.0181
Median household income	0.0197*	0.0195*	0.0072	0.0067	−0.0038	0.0139*
Cumulative EVI	0.1431*	0.1684*	0.1581*	0.1252*	0.1305*	0.1540*
Percent grass cover	−0.4163	0.3668*	−0.2401*	−0.2815*	−0.1511	−0.5775
Total precipitation	−0.000552*	−0.000498*	−0.000498*	−0.00071*	−0.000458*	−0.00064*
Average daily maximum temperature	0.02865*	0.0207*	0.02898*	0.0302*	0.02831*	0.02952*
First-tier usage block allocation per household	0.0088*	0.0166*	0.0091*	0.0074*	0.0096*	0.0082*
ln(First-tier block rate)	−0.1878*	−0.1118*	−0.2141*	−0.2459*	−0.1335*	−0.2390*
ln(Second-tier block rate)	−0.0697*	−0.0800*	−0.0722*	−0.0450*	−0.1025*	−0.0274*
R^2	0.895	0.845	0.909	0.913	0.890	0.904

*Significance at the 5% level.
SFR = single-family residential; EVI = enhanced vegetation index.
Source: Data from Mini (2013).

by the city system, as well as potential new inputs. The City of Los Angeles Bureau of Sanitation currently collects solid waste from single-family homes and multifamily housing complexes of four or fewer units. It separately collects trash, comingled recyclables, and yard waste from the city's 540,000 single-family homes and 220,000 small multifamily complexes (note the difference in SFR home numbers for Bureau of Sanitation [540,000] and LADWP [480,000]). These tonnages are reported for each of six waste sheds that span the city. Private waste haulers provide collection services to the city's commercial properties, which include multifamily housing complexes of five or more units as well as commercial, industrial, and institutional properties. Currently, there are approximately 45 haulers providing such services that report aggregate collection data to the city for purposes of assessing a state-mandated fee. Solid waste tonnages collected by private haulers are not reported at any consistent unit of geographic aggregation smaller than the city in its entirety. Additional discussion of the structure of solid waste management in the city of Los Angeles may be found in Murphy and Pincetl (2013). The remaining 87 cities within the county employ a mix of solid waste hauling arrangements. In nearly all cases, waste collection data are reported to cities for their full service territory, without any higher resolution available. Finally, the county of Los Angeles has jurisdiction over unincorporated county territory. It divides this area into a system of approximately 100 waste sheds.

Using publicly reported data, researchers estimated solid waste flows for each city as well as for the unincorporated county territory. All data are made available through the County of Los Angeles Department of Public Works Solid Waste Information Management System (SWIMS). SWIMS archives monthly solid waste disposal tonnage data for each city and for the unincorporated county. Data are continually updated as they are provided to the County Department of Public Works.

Discussion and Illustrative Results

Building Energy Consumption and Greenhouse Gas Emissions

Results from the analysis of building energy consumption found the age of the building and household income levels significant predictors of electricity use and hence GHG emissions. Emissions resulting from electricity use are shown in table 1.

We found that newer buildings (built between 1980 and 2000) tend to consume more energy than older buildings. This is a significant and counterintuitive finding because these buildings have implemented state-of-the-art (at the time) California Title 24 energy conservation standards. The research shows that increased energy use is correlated to the increased floorspace trends that have been observed in the past half century; it is also possible that part of the increase can be attributed to the increased use of more modern, but also more pervasive, appliances and air conditioning that undercut efficiency gains. Indeed, this finding confirms other emerging studies and analysis showing increased energy use in energy-efficient buildings (Kahn et al. 2013). Combining these results with those from the infrastructure assessment may reveal unintended consequences of state policy and suggest new strategies for energy-use reduction at the building level, highlighting the importance of coupling UM with policy drivers. Fortunately, electricity consumption declines for buildings built or renovated after 2000, compared to the buildings built in the previous era (1981–2000), perhaps as a result of the latest energy efficiency codes. Unsurprisingly, the size of the housing units is an important predictor of the electricity consumption per capita: Individuals that live in larger homes tend to use more electricity, and the effect is amplified for individuals that live in a house with a pool. When coupled with sociodemographic information obtained from the 2010 Census, the patterns of electricity use show a statistically significant and positive correlation with higher incomes.

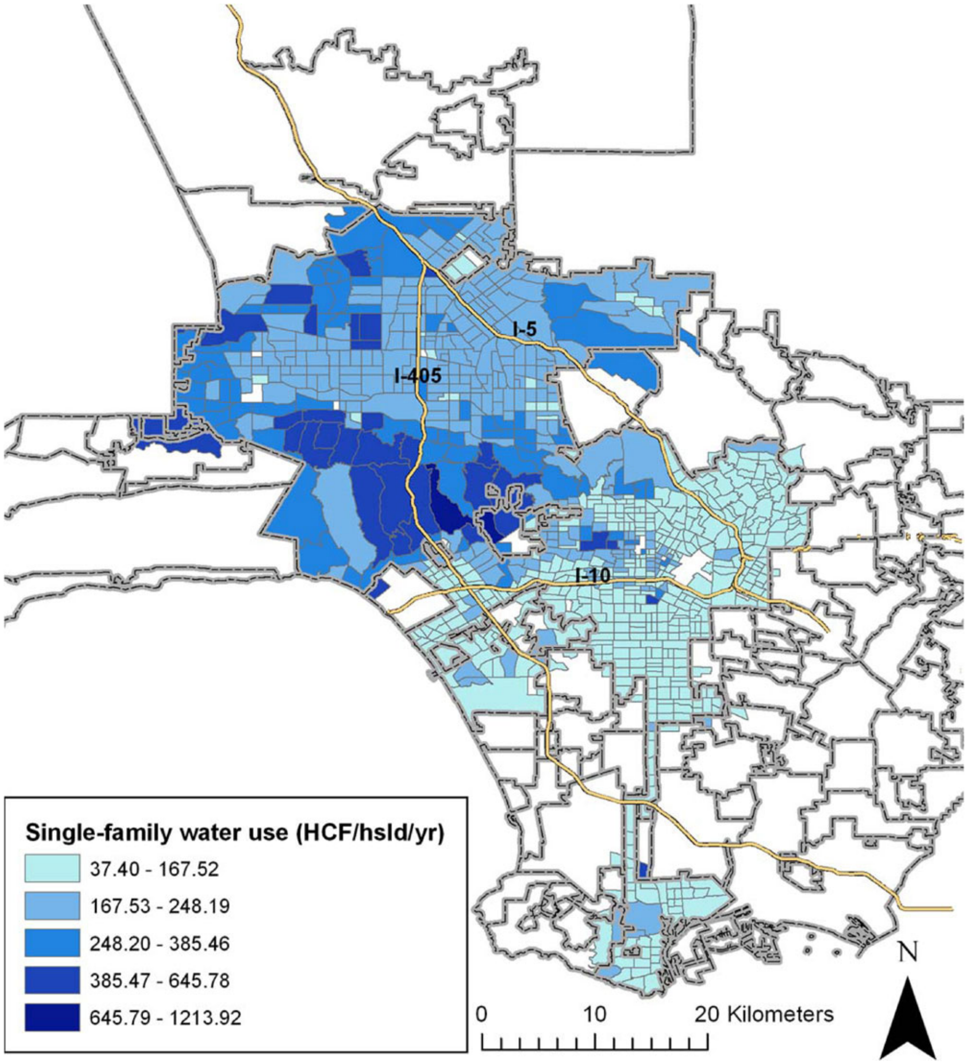

Figure 2 Ten-year average single-family residential water use by census tract for Los Angeles.

This research demonstrates that understanding the energy use by different types of buildings, and their building shell, can result in better energy conservation programs. Indeed, having established baselines of energy use, the addition of a layer of data showing energy conservation investments would then allow assessment of which types of investments have worked, where and by what building, sociodemographic, climate or other characteristics, and what has not been successful. Energy conservation and efficiency program investments by parcel are thus another important data need in this type of research, but also difficult to obtain from the utilities. This analysis was conducted with ZIP+4 energy use for the city of Los Angeles and then modeled for Los Angeles County.

Water Consumption in Los Angeles Over Time

Results show a strong correlation between income and water use as well as overall declines in water use over time (Mini 2013). As with electricity use in Los Angeles, there is a pattern of greater consumption of water with greater income. Results also found higher price elasticity for lower incomes, even in a lifeline tier. Those within the lowest-tier users (lifeline rate) conserved proportionately more water when pricing reflected summer scarcity than those in the second tier. Thus, even with tiered water pricing, lower-income residents who pay less for water than the next tier conserve more water than those paying more for their water (showing a nonsurprising higher price sensitivity). Research also showed that mandatory conservation—restricting days and times outdoor irrigation was allowed—was more effective in reducing water use than voluntary programs. Table 2 shows the dependent and independent variables for residential water consumption, and table 3 shows the regression results.

This analysis found that even with an estimated 22% water-use reduction, existing vegetation still did well, suggesting that there is a great potential for water savings that can occur even without changing the landscape to more climate-appropriate plantings (Mini 2013). This also implies that with

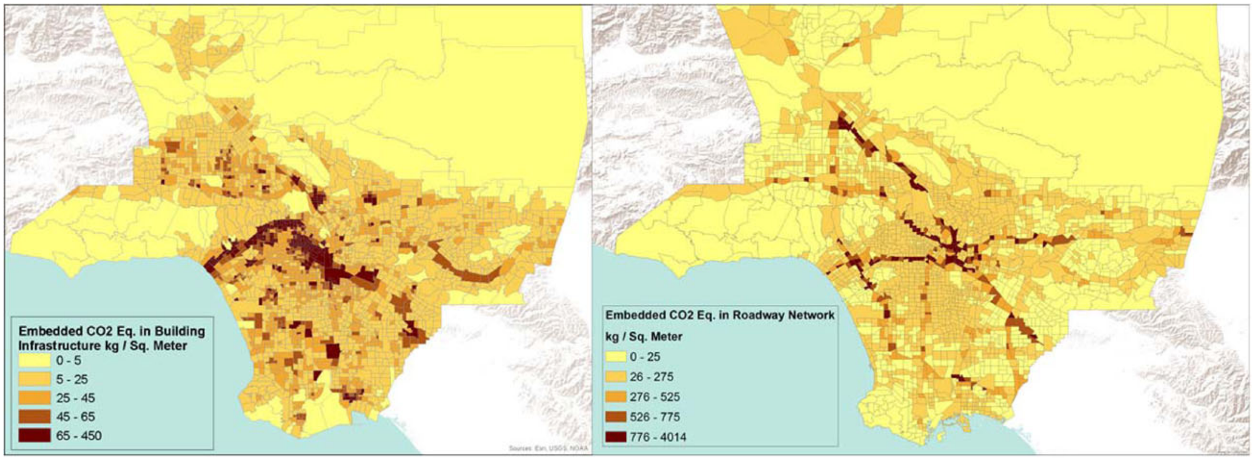

Figure 3 Embedded greenhouse gas emissions in buildings (left, kg CO_2-eq/m^2) and roadways (right, kg CO_2-eq/m^2). kg CO_2-eq/m^2 = kilograms carbon dioxide equivalent per square meter.

climate-appropriate plantings, there is even greater potential for water savings in the single-family sector. One of the greatest challenges for sustainability is to reduce consumption. Consumption data coupled with information on rate structures connect metabolic flows to who is using the water in what quantities. Energy and water findings show that the target audience for reductions in the residential sector are residents with higher incomes. These findings can provide multidimensional empirical data for policy makers relative to rates, as well as water conservation programs and mandates. This research also provides a methodology for estimating indoor and outdoor water consumption. Figure 2 displays 10-year average residential water use by census tract for the city of Los Angeles.

Solid Waste Flows

County solid waste flow analysis proved difficult. As noted above, not only is the structure of waste management in both the county and the city of Los Angeles highly complex (and further overlaid with state- and national-level requirements), but also data are highly aggregated and waste tonnages are not reported beyond what is sent to disposal facilities. As a result, analysis of solid waste was quite limited, compared to other flows and components of this study. Using available data, researchers were able to assess changes in disposal tonnages by individual city and for the unincorporated county territory over time beginning in 1995. Disposal tonnages were further disaggregated into landfilled waste and waste-to-energy (incineration) facilities. For example, between 2000 and 2010, the full county of Los Angeles (including all cities) reduced its disposal of municipal solid waste by more than 44%—from 11.21 to 6.24 million metric tons. The quantity sent to landfill decreased by more than 46% (from 10.71 to 5.71 million metric tons), whereas the quantity sent to waste-to-energy facilities increased by more than 8% (from 492,000 to 535,000 metric tons). Between 2000 and 2010, the city of Los Angeles reduced its disposal of municipal solid waste by more than 38%, from 3.43 to 2.11 million metric tons. The quantity sent to landfill decreased by more than 38% (from 3.35 to 2.05 million metric tons), whereas the quantity sent to waste-to-energy facilities decreased by 18% (from 74,000 to 61,000 metric tons). Finally, the unincorporated county decreased waste disposal by more than 27%, from 977,000 to 705,000 metric tons between 2000 and 2010. The quantity sent to landfill decreased by more than 27% (from 968,000 to 702,000 metric tons), whereas the quantity sent to waste-to-energy facilities decreased by more than 70% (from 9,000 to 3,000 metric tons). Subsequent analysis will attempt to relate disposal trends to city-level sociodemographic information.

As these summary statistics suggest, current waste management approaches in California have focused mainly on reducing the amounts of waste going to landfills because they are contested, near urban areas, and are costly to develop. There is little-to-no characterization of the waste flow by generator, nor of amounts per sector. In California, there are no good numbers on solid waste flows beyond what is sent to disposal facilities, neither at the comingled level nor by type of diverted flow. Further attention has not been given to reducing the generation of waste at the source or to reducing the net material throughput of the economy. Because recyclable materials are increasingly picked up as comingled for customer ease of disposal, reseparating materials becomes costly and mingled recyclables are dirtier and less directly reusable. They are therefore predominantly sent overseas (Lyons et al. 2009; Zhang et al. 2007; Puckett et al. 2002), where labor is less expensive and environmental protections weaker. Greater research into quantifying the GHG and environmental impacts associated with waste management and recycling are needed, as is understanding what kinds of waste and amounts are generated by which sectors. Analysis of the implications for long-term virgin material supplies in the United States is also needed.

County-level Embedded Infrastructure Impacts

The granular spatial-temporal assessment of embedded flows reveals inefficiencies in the rapid expansive growth of the county during the past 30 years. Older (and more centrally located) neighborhoods have larger embedded impacts per unit of land area as a result of their higher building densities, whereas per capita impacts in these high-density neighborhoods tend to be low. However, sprawling residential outward growth has led to the embedding of low-population-density impacts at the county fringe, which is dominated by large residential detached single-family homes. The net effect is that, across the county, the average embedded energy and GHG emissions per unit of floor area has remained fairly constant. This has occurred while the manufacturing of raw materials and construction practices have become more efficient. Approximately 70% of embedded building energy and GHG emissions occurred between 1930 and 1980. This implies that, since 1980, Los Angeles has been deploying new building infrastructure at a slowing pace and has instead focused on using and upgrading existing building infrastructure. A similar finding occurs for the embedded impact of roadway assessment. Figure 3 shows the embedded GHG emissions in buildings on the left and roadways on the right.

Results from the roadway assessment show that energy use and GHG emissions from initial construction are dwarfed in the long run by resurfacing activities that replace the wearing layers every 5 to 30 years. A pavement LCA model was developed for assessing the changing embedded impacts of roadway networks and, as with the building infrastructure analysis, includes the ability to assess impacts at high spatial (roadway link) and temporal (initial construction through repeated resurfacing) resolution.

The model builds on data from the PaLATE (see Horvath 2003) and creates a framework for assessing the deployment and resurfacing of roadway infrastructure in a region. For the county of Los Angeles, the embedded roadway analysis was joined with historical vehicle travel data to assess how infrastructure saturation may be contributing to peak travel experienced in the county starting around the turn of the century (Fraser and Chester 2013). Saturation of the infrastructure is a cascading impact that starts with freeways and arterials, but spills over to collector and local roadways. Through this geospatially explicit assessment (figure 3), it is possible to identify the locations and time periods in which these impacts are occurring.

Conclusions

This project, attempting to describe the urban metabolism of Los Angeles County, has combined countywide LCA of built infrastructure, specific data from the city of Los Angeles (4 million people) in the area of water and electricity use, county and city solid waste data, and the modeling of GHG emissions from electricity based on patterns of electricity use found in the city of Los Angeles. The different scales are, in part, a result of data availability, and the next phase of the project will be to both verify our current results and go beyond them with the parcel level electricity and natural gas data we have obtained that span 2006–2012 for the whole county. We will also obtain and integrate data on energy conservation and efficiency programs, as well as installed solar generation, which will help us develop accurate baselines of energy use from 2006 and to evaluate the success of energy conservation and efficiency programs by type. Moreover, coupled with recent climate downscaling work (Hall et al. 2013) for the Los Angeles region at a 2-kilometer resolution, we will be able to determine patterns of current energy use in the areas most susceptible to greater warming, their sociodemographics and building types, and to make policy recommendations about adaptation strategies. Our water analysis for LADWP will be expanded to include the commercial, multifamily, and industrial sectors.

By looking at cities as sociometabolic regimes with many interacting inputs and outputs that have real tangible and measurable impacts, researchers can begin to create a more complete description of a city's UM. This includes more specific accounting of inputs and outputs across people and space and the integration of social systems, policies, programs, funding, rules, and the economy that actually determine a city's metabolism. Further, as Huang and Chen (2009) and Boyden and colleagues (1981) point out, to make urbanization sustainable, we must understand the relationships between cities and their surrounding environment relative to resource consumption and create a socioeconomic metabolic approach. The biggest challenge going forward is to unravel the multiple drivers of the flows and sinks. From parking regulations to the oil depletion allowance and the structure of the mortgage markets, there are many forces that create current complex urban systems and may constrain change. Therefore, it is no longer sufficient to quantify flows; they are simply the reflection of societal priorities and organization.

From the research on Los Angeles (as with many other cities), it is evident that flows into cities and out of cities affect populations differently, and are accessed differently, depending on income, employment, geographical location, and a suite of other factors. By coupling the flows with such things as pricing, researchers can show how, as in the case of Los Angeles, lower-income residents have the highest water elasticity as a result of price sensitivity, and that if the policy goal is water-use reduction, programs must target water use by the more affluent. This, of course, ultimately becomes an issue of political decision making—as are many fundamental aspects of the structure of urban systems and their metabolism. They are matters of power and influence.

The lack of thorough and comprehensive reporting of solid waste flows is another example of social policy that has unequal outcomes, this time across the globe. The Los Angeles region sends its dirty recyclables to China, simply transferring the human burden of reclaiming resources to another country.

An expanded approach to UM transforms it from a high-level accounting of flows and sinks to a platform for transformational action. Such an evolution will require UM researchers to seek and demand better data for analysis as well as the willingness to couple multiple and sometimes disparate sets of data together, including urban history (how a city has grown) and political economy (the drivers of the economy). But, the challenges facing the planet's capacity to provide the resources and the pollution sinks going forward demand this next level of activity. By acknowledging UM as a sociometabolic system (Haberl et al. 2011), scholars and practitioners can quantify flows and connect them to how societies are organized and thus enable insights about necessary policy changes.

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